



The Spatial and Temporal Dynamics of Remotely-sensed Vegetation Phenology in Central Asia in the 1982-2011 Period

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Abstract

An understanding of present and past vegetation dynamics is essential to future reaction strategies to climate change, especially in developing regions. This study seeks to widen such knowledge by utilizing remotely-sensed normalized difference vegetation index (NDVI) data to compute phenology metrics for Central Asia in the 1982-2011 period. Spatial and temporal analysis was performed for nine phenological metrics and for sub-regions with consistent vegetation dynamics. A general increase of biomass was disclosed, except in bare deserts, and the growing season appears to be starting earlier. Despite of the dominant greening trend, deserts show inverse dynamics, possibly a sign of rising aridity.

Keywords: Phenology, vegetation dynamics, NDVI, GIMMS, Central Asia, SOS.

Introduction

Recent climate change has had a significant impact on various types of vegetation cover all over Central Asia, and will continue to do so [Lioubimtseva and Henebry, 2009]. Vegetation dynamics, especially phenology, are directly linked to climatic conditions. Thus analyses of phenological metrics may be employed as indicators of climate change [Lin et al., 2014; de Sherbinin et al., 2014]. A range of methods for monitoring phases of plant species and their temporal development has emerged to address the relations between climate conditions and vegetation cover [Fraga et al., 2014; Xie et al., 2008 and references herein for a review]. According to Cleland et al. [2007] these methods include: (1) species-level observations; (2) atmospheric monitoring of carbon dioxide concentrations as an indication of the timing of photosynthesis-driven carbon uptake; and (3) remote sensing of ecosystem production. The third approach was employed in this study.

The most widely-used indicator, derived from satellite measurements and closely related to vegetation activity, is known as the normalized difference vegetation index (NDVI) [Tucker,

1979]. NDVI time series may be used to derive phenology metrics defining events in vegetation growth, especially on regional and global scales [Reed et al., 1994; White et al., 2009]. Jeong et al. [2011] described shifts in the start and end of the growing season in the northern hemisphere. Their results indicated that the start of the season (SOS) advanced by 5.2 days in 1982-1999 but by only 0.2 days in the 2000-2008 period. End of season was delayed by 4.3 and 2.3 days in the two periods respectively. In contrast to this hemispheric trend, the part of the Central Asia north of Kazakhstan did not experience such an advanced SOS [Jeong et al., 2011].

Central Asia (CA) is a relatively large and sparsely-populated region so, in the absence of any other consistent data, remote sensing is often used for its mapping. Recent work includes land-cover mapping [Klein et al., 2012], crop classification at field level [Conrad et al., 2010], water use [Conrad et al., 2007] and mapping of large, irrigated areas [Machwitz et al., 2010]. NDVI trends in CA and their relation to temperature and precipitation have been assessed by Propastin et al. [2008b]. A significant increase in NDVI was indicated for 35% of the vegetated area of CA during the 1982-2003 period, largely around the spring season, and upward trends were significantly correlated with higher spring temperatures and summer precipitation.

Kariyeva and van Leeuwen [2011] investigated relations between vegetation dynamics and a number of environmental factors (temperature, precipitation, elevation, and soil carbon content) in three types of CA landscapes, excluding agricultural land. They concluded that their given factors play roles that vary with season and landscape. Thus, in terms of SOS, temperature regime was the most significant factor for steppes, except in summer; temperature and precipitation were predominant in desert landscapes; and elevation was most important in mountainous regions.

Further, Kariyeva et al. [2012] investigated the temporal variability of the peak of the season and evaluated the impact of climate on vegetation phenology, including irrigated and rain-fed agriculture. The most important variable emerged as spring temperature, which indicates that higher temperatures in the near future will be responsible for an earlier, longer growing season. Kariyeva and van Leeuwen [2012], in a comparison of situations before and after the Soviet collapse, showed that, quite apart from climate variability, the role of land management and socio-economic factors had significant influences on vegetation phenology. This accords with the findings of de Beurs and Henebry [2004] in their study of changes in Kazakhstan in relation to shifts in governance after the collapse of the Soviet Union, in which they discriminated clearly between climatic and anthropogenic factors.

Gessner et al. [2012] showed that vegetation development is sensitive to precipitation over 80% of the Central Asian land surface, and that this sensitivity is particularly acute in areas with 100-400 mm of annual rainfall. Moreover, rainfall-NDVI interaction emerged as strongest for precipitation anomalies integrated over 2-4 months, with a temporal lag of 1-3 months.

The possible impacts of climate variability and environmental changes in CA are discussed in detail in Lioubimtseva et al. [2005] and Lioubimtseva and Henebry [2009]. They attribute the particular vulnerability of the region to its large areas of desert, relative underdevelopment, and the traumatic social, economic and institutional upheaval following independence. Further, a projected warming of about 2°C to 3°C by 2050 will further increase the aridity of the region [Lioubimtseva, 2015].

The aim of this paper is to present the vegetation dynamics of Central Asia as expressed by spatial and temporal variability in land surface phenology represented by a set of

nine different phenological metrics covering the 1982-2011 period, and to establish any significant trends. In terms of existing studies, this contribution extends the analysis of NDVI time series to 30 years and focuses on phenology metrics rather than on NDVI alone. The set of nine different metrics and trends within it may be more robust than individual aspects of phenology taken alone. Finally, this trend analysis is spatially related to sub-regions with relatively consistent vegetation dynamics. Results derived for such homogeneous areas may provide data that are more spatially accurate and better applicable, thus partially overcoming the disadvantages of primary remote sensing data. This could better serve the needs of current land management in the region.

Region and data

The Central Asian region

For the purposes of this study, Central Asia is defined as the five post-Soviet republics of Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan. The area covered lies between 34°57'30"N and 55°47'30"N and 46°12'29"E and 87°52'29"E (Fig. 1).

Central Asia's climate is highly continental. The annual temperature means show a clear south-north gradient from 20 °C in Turkmenistan to 2 °C in the north of Kazakhstan [Mannig et al., 2013]. This is modified by orography effects of mountain ranges, especially by Tien Shan on the east of the region and Altai in the north-east where mean annual temperatures are lower. Precipitation is very low (from only 30 mm annually) in arid parts of Turkmenistan and Uzbekistan. From there, precipitation gradient increases up till 500 mm per year in the north Kazakhstan. Only mountain regions of Tajikistan and Kyrgyzstan have annual rainfalls higher than 1000 mm.

The study area may be described in terms of the original distribution of vegetation species prior to major land-use changes. Such world terrestrial ecoregions were defined by Olson et al. [2001], and a distinct north-south distribution pattern exists within the study area. From north to south, the major ecoregions are Kazakh forest steppe, steppe and semi-desert, followed by the Central Asian northern desert, the southern desert and the Badkhyz and Karabil semi-deserts. Western Kazakhstan is made up of the Pontic steppe and the Caspian lowland desert. The Kopet Dag semi-desert and woodland and forest steppe occur in the south of Turkmenistan. Beyond these zonal categories are the Central Asian riparian woodlands and mountainous regions, largely subject to elevation stratification. The Altai Mountains lie in north-eastern Kazakhstan, with steppe and semi-desert, montane forest and forest steppe, and alpine meadow and tundra. Much of Kyrgyzstan and Tajikistan is taken up by the Tien Shan and Pamir mountain ranges, containing Middle Asian montane woodlands with steppe, open woodlands, alpine desert and tundra.

The current distribution of the main land cover categories in CA was mapped by Klein et al. [2012] using MODIS data at a spatial resolution of 250 x 250 m. Rain-fed agriculture may be found in the north of Kazakhstan, while most of the other parts of the country are covered in grassland steppe. Open shrubland predominates in the mixed area of transition to the south. Bare soils with occasional shrubs and sparse herbaceous cover prevail in the southern desert and semi-desert areas of Central Asia, except for the densely-inhabited, irrigated areas with intensive agriculture and thick vegetation. The mountain regions of Tajikistan and Kyrgyzstan are classified mostly as grasslands, with ice and snow at higher elevations. The only forested part of any significant extent is made up of the needle-leaved

forest of the Altai, part of the Siberian conifer forest.

The original ecoregions after Olson et al. [2001] and a land-cover map from 2009 [Klein et al., 2012] were combined into smaller spatial units (sub-regions) in Gessner et al. [2012]. The spatio-temporal analysis of phenological metrics presented here employs these sub-regions. Detailed definitions of the sub-regions appear in the following section.

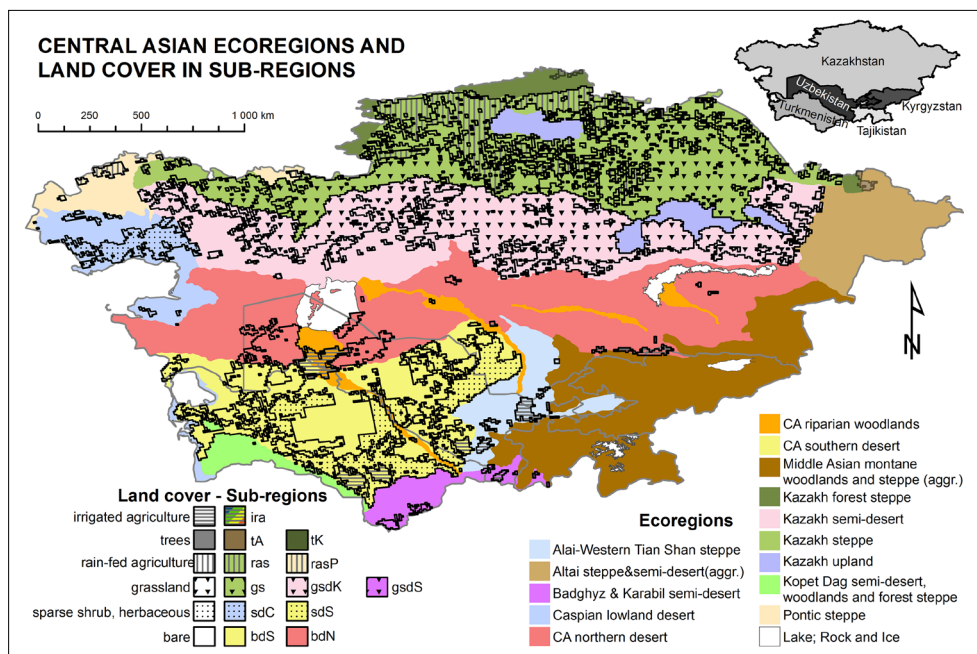


Figure 1 - Central Asian sub-regions. Sub-regions as defined by Gessner et al. [2012]; intersections of main terrestrial ecoregions (color) after Olson et al. [2001] and land cover (pattern, Klein et al., 2012). For sub-region abbreviations, see Table 1.

Satellite Data

This study employs a Global Inventory Modelling and Mapping Studies (GIMMS) dataset provided by the University of Maryland Global Land Cover Facility [Pinzon et al., 2006; Tucker et al., 2013], in its third generation (NDVI3g) covering the 1981-2011 period. It is derived from the Advanced Very High Resolution Radiometer (AVHRR) instrument carried by the National Oceanic and Atmospheric Administration (NOAA) satellite series 7, 9, 11, 14, 16, 17 and 18. The spatial resolution is 8×8 km (0.07272727°) with a bimonthly temporal resolution. The NDVI is produced as a 15-day maximum value composite. The dataset has been corrected for possible biases in NDVI values arising from calibration methods, viewing geometry, volcanic aerosols and other effects not related to vegetation change [Tucker et al., 2005; Pinzon et al., 2006].

The GIMMS dataset is scaled, i.e. the original NDVI values are multiplied by 10000. Metadata facilitate quality control and identification of the date of data acquisition of each pixel in the composite. Data are available in global (except for Greenland and Antarctica) and continental data files. For this study, the GIMMS data for the CA region were processed and re-projected to geographical coordinates.

Methods

Definition of sub-regions

Sub-regions with relatively consistent vegetation dynamics were employed for the interpretation of phenology metrics and analysis of trends. Sub-regions were derived after Gessner et al. [2012] and their delineation follows three principles. First, sub-regions cover only areas with 100-400 mm of annual precipitation, which avoids bare deserts (no phenology) and humid, mostly high-mountain regions (with very diverse phenology). Second, each sub-region belongs to only one ecoregion [Olson et al., 2001] and one of the main land-cover classes [Klein et al., 2012]; Third, to address homogeneity, at least 60% of the 8 x 8-km cells (well within GIMMS data spatial resolution) must be covered with the same land cover class at a resolution source layer of 250 x 250 m. Moreover, only cells that border on five or more cells of the same class were considered, in order to allow for geolocation uncertainties. The basics of the individual sub-regions appear in Table 1.

Table 1 - Basic characteristics of sub-regions in the study area. Classification of ecoregions follows Olson et al. [2001] and land-cover classes follow Klein et al. [2012]. The sub-regions, as adopted from Gessner et al., [2012] appear in Figure 1.

Abbr	expansion	land cover class (definition)	ecoregion	area km ²
ira	irrigated agriculture	irrigated agriculture (cultivated and managed area, irrigated)	Central Asian riparian woodlands	53222
tA	tree Altai	evergreen needle-leaved trees (>65%)	Altai montane forest and forest steppe	2193
tK	tree Kazakh	deciduous broadleaved trees (>65%)	Kazakh forest steppe	1181
ras	rain-agriculture steppe	rain-fed agriculture (cultivated and managed area, not irrigated)	Kazakh steppe	143135
rasP	rain-agri. steppe Pontic		Pontic steppe	7844
gs	grass steppe	grassland (herbaceous 15-100%, 3cm-3m)	Kazakh steppe	342023
gsdK	grass semi-des Kazakh		Kazakh semi-desert	400052
gsdS	grass semi-des South		Badghyz and Karabil semi-desert	7001
sdC	shrub desert Caspian	sparse shrubs and sparse herbaceous (shrubs 1-15%, herbaceous 5-15%)	Caspian lowland desert	44450
sdS	shrub desert South		Central Asian southern desert	184380
bdN	bare desert North	bare area (<4% vegetation cover)	Central Asian northern desert	52463
bdS	bare desert South		Central Asian southern desert	86961

The sub-regions consist of spatial units that exhibit various densities of vegetation cover (bare soil, sparse shrub and sparse herbaceous, grassland, broadleaved trees and needle-leaved trees). Two categories of agriculture (rain-fed and irrigated) are both associated with relatively dense vegetation cover and strong anthropogenic influence. Of twelve sub-regions, five were selected for detailed analysis: shrub desert Caspian (sdC), rain-fed agricultural steppe (ras), grass steppe (gs), bare desert south (bdS) and irrigated agriculture (ira). This selection was designed to include one sub-region from each land cover class (except “tree” classes, since their areas are very small) and to obtain an equal distribution across all of Central Asia.

NDVI filtering and phenological metrics

Wide temporal variability is often a feature of NDVI time series. This is not confined to only vegetation dynamics, but frequently involves noise arising out of, for example, calculation method (maximum index value over a 15-day period). Thus original data have to be filtered before analysis. TIMESAT software was used for filtering time series and deriving phenology metrics [Jönsson and Eklundh, 2002, 2004]. The principles of derivation of phenological metrics for this study appear in Figure 2.

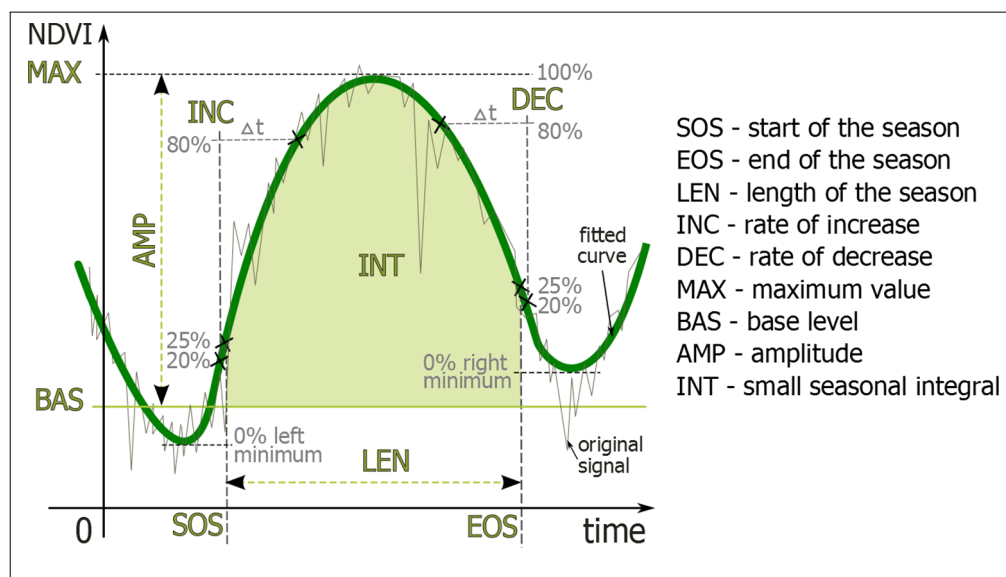


Figure 2 - Annual variability of original (thin line) and filtered (thick line) NDVI values and definition of the nine phenological metrics used in this study; adapted from Eklundh and Jönsson [2012]. See text for abbreviations of individual metrics.

Several approaches may be taken to the derivation of phenological metrics and noise reduction in NDVI time series, none of them of absolute advantage [White et al., 2009]. In this study, the definitions of individual metrics and approaches to the results were adapted after Bohovic et al. [2011]. Three filters were considered: the Savitzky-Golay filter [Chen et al., 2004]; asymmetrical Gaussian function fitting; and double logistic fitting [Eklundh

and Jönsson, 2012]. A relative threshold (percentage of seasonal amplitude) was then chosen in order to derive SOS and subsequently other phenological metrics. For large and relatively heterogeneous areas, a relative threshold guarantees comparability of results. After comparing the three smoothing methods and three relative thresholds (10%, 25% and 50%), Gaussian fitting at a 25% threshold was chosen, based upon a correlation matrix of nine options (three filtering methods with three thresholds). Moreover, the Gaussian filter with a 25% threshold provided stable results for the whole region and for all vegetation types.

Nine phenology metrics were calculated for the description of vegetation dynamics; mathematical definitions of them appear in Eklundh and Jönsson [2012]. Details are presented in Figure 2 and below. The start of the season (SOS), usually the beginning of spring, i.e. greening of vegetation, was computed first. This metric was forced to only one season per year (first season if there was more than one season). Thus, herein SOS is the day in a given year when the NDVI value reaches 25% of the difference between the first minimum and the seasonal maximum (MAX) of all NDVI values.

The end of the season (EOS) is the day of the year upon which the NDVI signal falls to lower than 25% of the difference between MAX and the right-hand minimum. The difference between SOS and EOS defines the length (LEN) of vegetation season. LEN is interpreted as the part of the year with suitable conditions for vegetation growth. Rate of increase (INC) at the beginning of the season and rate of decrease at the end of the season (DEC) are computed as the ratio of the difference between the left (right for DEC) 20% to 80% NDVI values and the corresponding time difference. DEC is positive as it is computed from absolute values. Higher values of INC (DEC) are characterized by a higher increase (decrease) of greenness within a given time-span i.e. less time is needed for a given change of greenness. Thus INC and DEC can be interpreted as measures of vegetation dynamics at the beginning and at the end of the season.

Further seasonal NDVI characteristics are maximum value (MAX), base level (BAS) as an average of left and right minimum, and finally amplitude (AMP) as the difference between MAX and BAS values. The small seasonal integral (INT) integrates the difference between the function describing the season and the base level (unlike the more usual integral computed from zero level) from SOS to EOS. During the growing season, AMP gives an indication of vegetation development, BAS represents vegetation greenness at its minimum performance (left and right average). MAX is the sum of these two metrics (BAS+AMP) and therefore independent of minimum NDVI values outside the season (which contain the most noise in the index). INT determines the degree of vegetation greenness during the entire season as an integral value between NDVI-line and baseline. It is therefore related to BAS and also dependent on the annual course of vegetation development rather than a single peak of vegetation greenness (MAX).

Satellite-based phenology metrics are relative rather than absolute measures, and cannot thus be directly compared with real in situ phenology [White et al., 2009]. Interpretation of metrics cannot avoid generalization of the phenological cycle. However, the measurements do express the general dynamics of phenology on a regional scale.

Spatial variability and trend analysis

Phenological metrics were computed for each year (season) of the 1982-2011 period and

descriptive statistics were used to characterize their typical spatial variability within the study area by means of box-plots. Differences among individual sub-regions were further tested by one-way analysis of variance (ANOVA). Subsequent evaluation of differences used the Bonferroni test, which addresses the problem of multiple comparisons that arises when simple tests (e.g. the t-test) are used for comparison between a higher number of variables, where some tests will have p-values less than 0.05 purely by chance, even if the null hypotheses (no difference) actually hold.

Investigation of trends for twelve sub-regions (Tab. 1) and nine phenological metrics (Fig. 2) were analyzed, generating a total of 108 combinations. For each sub-region, a time series of average phenological metrics was computed as the mean value of all cells belonging to the sub-region per year. The time series were addressed in terms of anomalies from the mean of the whole 1982-2011 period and linear trends were fitted to the anomaly series.

Two methods were used to estimate parameters for the trend line. The first encompassed ordinary least square regression. The statistical significance of the computed trends was tested using ANOVA and F-test. A coefficient of determination (R^2) was used to express any variance in the time series that may be explained by linear trends in the phenological metrics. This parametric method of linear regression relies on a number of assumptions (linearity, homoscedasticity, normality, independence of residuals, serial correlation) that are not frequently fulfilled in environmental time series [Wilks, 2011]. These assumptions were checked to assure they are not being violated in NDVI time series. The linear trend was also addressed by Mann-Kendall test with Sen's slope estimate [Sen, 1968]. This non-parametric method chooses the median slope among all lines through pairs of two-dimensional sample points. Compared to linear regression, this approach is not sensitive to outliers and may be used for skewed or heteroscedastic data.

Results

Spatial variability

The main features of spatial variability appear in Figure 3, which presents the mean spatial distribution of phenological metrics in the study area (left) and box-plots summarizing characteristic values of metrics for individual sub-regions (right). Most of the variables demonstrate clear dependence on latitude (they vary north to south) and also upon altitude. The spatial distribution of variables is also modified in response to more local effects and anthropogenic factors, as described below.

The day of SOS (Fig. 3a) shows a general gradient starting from early February in the south-west and south-east of Turkmenistan, continuing in the Karakum and Kyzylkum deserts and the south-east of Kazakhstan in March. On the steppe, the start of vegetation occurs largely during April, with a clear pattern indicating a later date from south to north. This does not apply to the irrigated areas, which all start about 30 days (Khorezm, Kzyl-Orda, Amu Darya delta), or even 40 days (Mary and Tedjen areas in Turkmenistan) later than the surrounding non-irrigated areas. This results from anthropogenic management of vegetation in irrigated regions. Only in the Fergana valley is SOS earlier than in the surrounding mountainous areas. The latest start of vegetation activity occurs in the sub-regions covered with trees and in the mountains - as late as May or June for the higher parts of the Pamir. The highest inter-annual variability is found in deserts and semi-deserts, where SOS depends strongly upon comparatively isolated precipitation events.

Early summer is not too soon for end of season (EOS) in the driest parts of Central Asia (Fig. 3b). Nowhere is there a difference of more than one month between regions. The highest variability is in the Caspian lowland desert, while the lowest may be observed in irrigated areas controlled by scheduled agricultural land management.

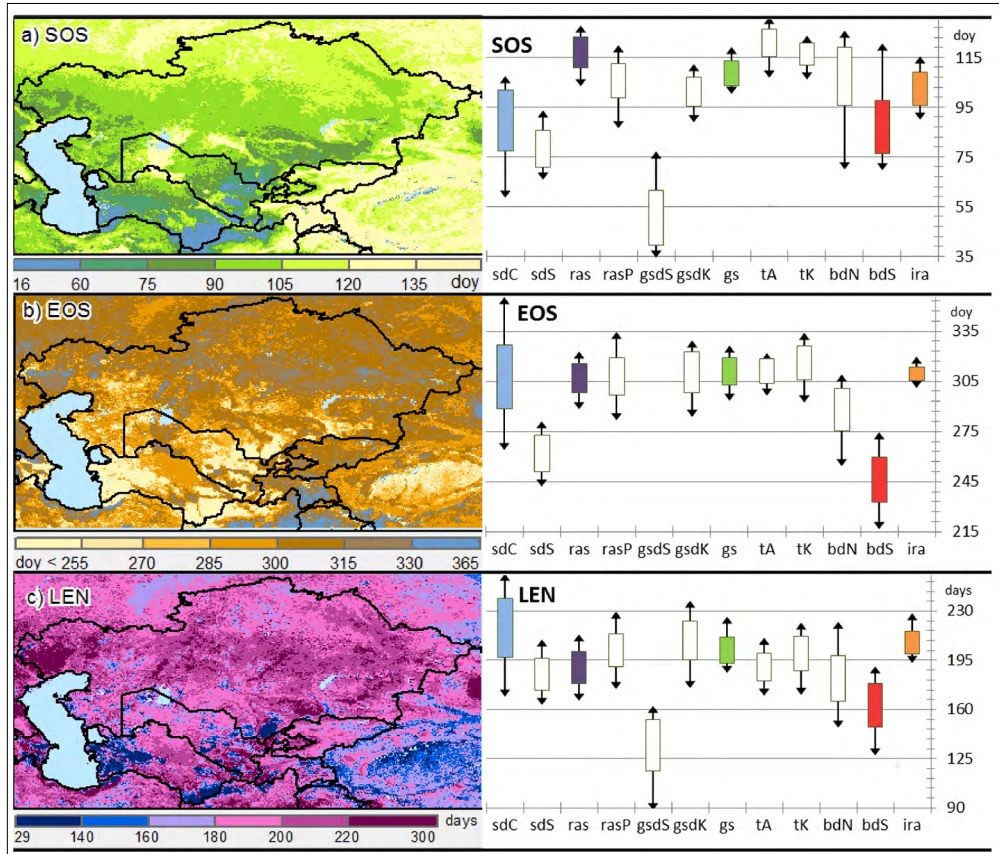


Figure 3a-i (Continued on the next page) - Spatial variability of nine phenological metrics in Central Asia, 1982-2011 (a-c). See text for definition of metrics (left) and box-plots (right). Square is mean \pm standard deviation, arrows indicate minimum and maximum values of series for individual sub-regions (see Fig. 1 for their delimitation and Tab. 1 for abbreviations); the fill colors of selected boxes correspond to Figure 4.

The length of season (LEN) (Fig. 3c) lasts only 3-4 months in desert areas, which respond swiftly to the growth-limiting factor of critical water availability. Shorter seasons may be found in the higher mountains (about 150 days). In most of the region, vegetation activity lasts about 195 days a year with no major difference between human-managed and natural ecosystems. The longest vegetation season occurs among the small shrubs of the Caspian desert.

INT, the integral of NDVI values above baseline for the season (Fig. 3d) reveals a distinct gradient from the south to the north of Kazakhstan. High values of INT may be found in

agricultural areas for dense crops and in the mountains for tree canopies. Bare areas and forests have very small inter-annual differences, in contrast to shrubs and grasslands with the highest interannual variability.

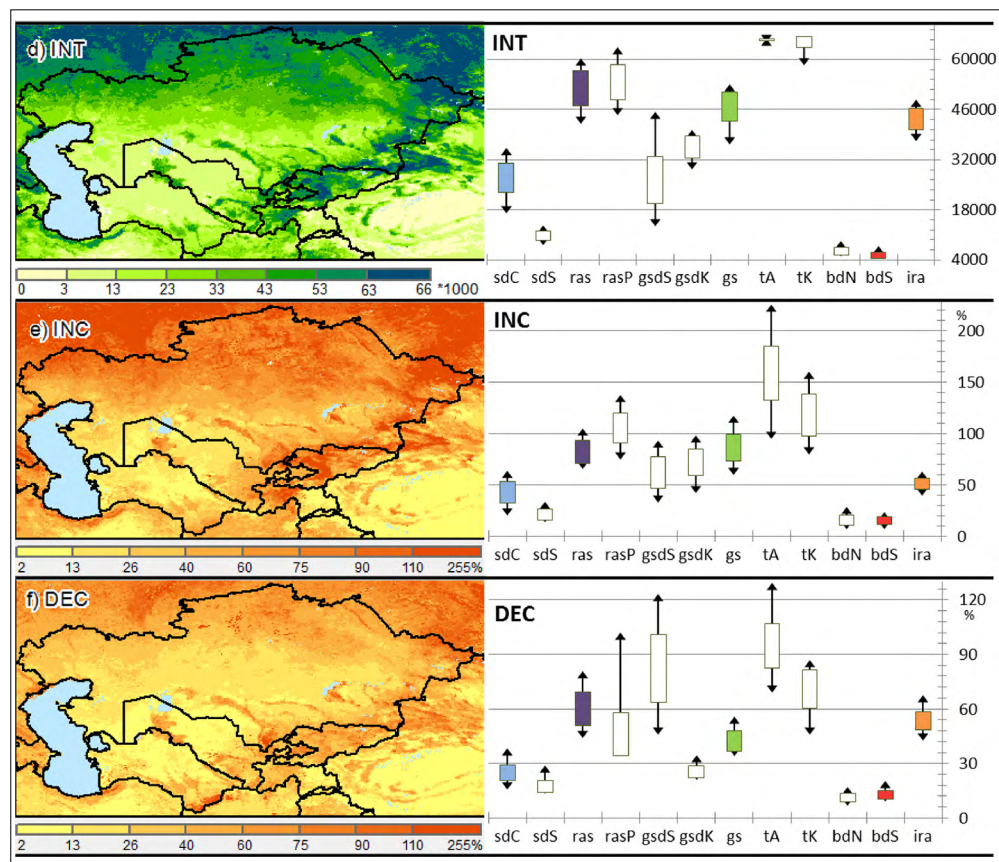


Figure 3a-i (Continued from preceding page and on the next page) - Spatial variability of nine phenological metrics in Central Asia, 1982-2011 (d-f). See text for definition of metrics (left) and box-plots (right). Square is mean \pm standard deviation, arrows indicate minimum and maximum values of series for individual sub-regions (see Fig. 1 for their delimitation and Tab. 1 for abbreviations); the fill colors of selected boxes correspond to Figure 4.

INC (Fig. 3e) may be interpreted as the rate of change of NDVI at the beginning of the season. It shows a similar pattern to INT, implying that biomass has a dominant effect in relation to time in the vegetation development phase. In contrast, DEC (Fig. 3f) is generally much lower than INC and the patterns of DEC for the sub-regions also differ from those of INT. This means that the time factor is more important in DEC than in INC, presumably since senescence is milder and slower than the onset of greening. This applies in general to the whole of Central Asia, except the bare areas and irrigated agricultural areas, where senescence is as steep as onset.

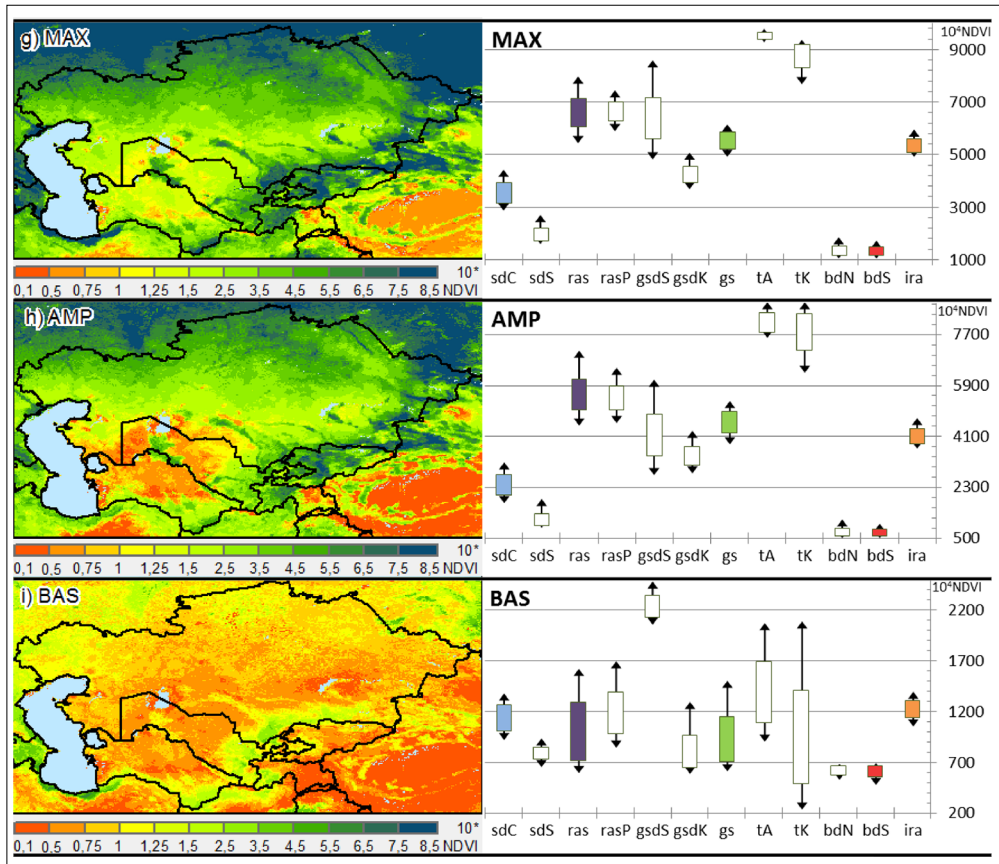


Figure 3a-i (Continued from preceding page)- Spatial variability of nine phenological metrics in Central Asia, 1982-2011 (g-i). See text for definition of metrics (left) and box-plots (right). Square is mean \pm standard deviation, arrows indicate minimum and maximum values of series for individual sub-regions (see Fig. 1 for their delimitation and Tab. 1 for abbreviations); the fill colors of selected boxes correspond to Figure 4.

The maximum value (MAX) and the amplitude (AMP) of vegetation seasonality (Fig. 3g, h) show very similar patterns. Both differ greatly across Central Asia and their values follow water availability in the region. The lowest values occur for the Usturt Plateau, the Aralkum, Karakum, Kyzylkum and High Pamir. Where agricultural land is irrigated, NDVI values are very stable over time and considerably higher than those for their surrounding areas. Overall, the values cover a wide range from the south to the north of Kazakhstan. BAS (Fig. 3i) is clearly related to conditions in the Central Asian ecosystems. The lowest levels can be observed for the Pamir mountains and on bare salinized soils around the Aral Sea and Lake Balkhash, followed by other mountainous areas, deserts, semi-deserts and steppe. The highest inter-annual variability of BAS occurs in agricultural areas and tree-covered sub-regions; there is accordingly a very low variability for bare soil.

Table 2 - The p-values of ANOVA Bonferroni tests among particular CA sub-regions for phenological metrics (just EOS, LEN, INT and BAS shown); p-values are provided only for those pairs of sub-regions that are not statistically different, while empty spaces indicate significant differences.

sub-region	EOS											
	sdC	sdS	ras	rasP	gsdS	gsdK	gs	tA	tK	bdN	bdS	ira
sdC	sdC		1.00	1.00		1.00	1.00	1.00	0.31			1.00
sdS		sdS										
ras		1.00	ras	1.00		1.00	1.00	1.00	0.13			1.00
rasP				rasP		1.00	1.00	1.00	0.33			1.00
gsdS					gsdS							
gsdK	0.83			1.00		gsdK	1.00	1.00	1.00			1.00
gs				1.00		1.00	gs	1.00	1.00			1.00
tA		1.00	1.00	0.07			0.06	tA	1.00			1.00
tK			0.45	1.00		0.59	1.00	0.61	tK			1.00
bdN		1.00	1.00					1.00		bdN		
bdS											bdS	
ira	0.19			1.00		1.00	1.00		1.00			ira
LEN												
sub-region	INT											
	sdC	sdS	ras	rasP	gsdS	gsdK	gs	tA	tK	bdN	bdS	ira
sdC	sdC				1.00							
sdS		sdS										
ras	0.90		ras	1.00								
rasP	1.00		0.05	rasP								
gsdS					gsdS							
gsdK		1.00				gsdK						
gs		0.97	1.00			1.00	gs					
tA								tA	1.00			
tK		0.31	1.00			0.92	1.00		tK			
bdN		0.19				0.06				bdN	1.00	
bdS		0.13								1.00	bdS	
ira	1.00			1.00				0.18				ira
BAS												

Differences in phenological metrics among individual regions were analysed more rigorously with ANOVA and Bonferroni tests. While ANOVA demonstrates the existence of significant differences in the metrics analysed as a whole (p-values of F statistics are under 0.001 for all metrics), the Bonferroni test enables disclosure of which particular pairs of sub-regions are significantly diverse. Results for all regions and four individual metrics (space restrictions) are summarized in Table 2.

In general, AMP, INC and INT exhibit the highest number of significant differences, clearly distinguishing sub-regions in terms of distinct and typical features, such as the way in which they characterize the productivity of the growing season rather than its duration. In contrast, CA sub-regions remain highly similar in EOS and LEN, with few significant differences in the end and duration of the growing season. This may be related to the anthropogenic factor in some sub-regions, such as those with irrigated agriculture (ira) or managed areas of Pontic steppe (rasP). Tree-covered tA and tK sub-regions also exhibit a higher degree of similarity to other sub-regions in LEN and EOS. On the other hand, grass semi-desert sub-region (gsdS) and bare desert sub-regions (bdN, bdS) exhibit the most highly differing values in the phenological metrics analysed with respect to values for other sub-regions.

Trend analysis

The main results of trend analysis appear in Table 3. Of 108 combinations of metrics and sub-regions, 53 series (49%) show significant trends at a 90% level of confidence. Of the 53 series, a total of 45 series (85%) demonstrate significant increase/decrease when addressed by both methods - ordinary least square regression and Sen slope estimate. Moreover, these significant increasing/decreasing tendencies move in identical directions.

SOS dates exhibit decreasing linear trends for all sub-regions, indicating a progressively earlier start to spring from 1981 to 2011. However this decrease is statistically significant for only the two sub-regions in which this shift is highest. Similarly, a slight shift towards earlier EOS can be found for most sub-regions, except where tree-covered (tA, tK). There is a significant positive trend in three sub-regions resulting in prolonged LEN. However, LEN values decrease slightly for other sub-regions.

The BAS metrics show relatively high and statistically significant negative trends for eight sub-regions, which may represent a general decrease in greenness for the winter season in major parts of Central Asia. On the other hand AMP and MAX values indicate increasing tendencies that are statistically significant in eight and six sub-regions respectively. AMP is dependent on BAS values, thus opposite trends in ras, rasP, gsdK, gs, tA and tK may be partially intrinsic. However MAX, which is not linked to BAS, shows the same trends as AMP, albeit with lower values. This indicates that the dependency link between AMP and BAS may be responsible for only part of the relatively high and significant positive trend of AMP in the sub-regions mentioned. This sign of rise of biomass productivity is underlined by a rising trend in INT values that is significant for seven sub-regions of non-desert Central Asia. In contrast to the more humid regions, bare areas (bdN, bdS) in deserts show insignificant and low decreases in productivity (INT, MAX, AMP) with a significant decrease in BAS, all of which may be an indication of ongoing desertification. Trends in the irrigated agricultural sub-region (ira) differ significantly compared with those in the neighbouring sub-regions with natural water supplies. A significant shift towards an earlier onset of SOS and a longer vegetation season (LEN) also results in an increase in green biomass (INT).

Table 3 - Linear trends (mean change/10 years) in phenological metrics in Central Asian sub-regions in the 1982-2011 period; significant trends at 90% level confidence appear in bold italics; see text for abbreviations for metrics and Table 1 for abbreviations for sub-regions.

10 years lin. trend change		10 years Sen's Slope estimate		SOS [days]		BAS [10°NDVI]		INT [10°NDVI]		MAX [10°NDVI]	
ira	irrigated agriculture			-3.9	-4.7	23.2	28.6	1714.7	1789.1	81.0	64.2
tA	tree Altai			-1.0	-1.2	-205.8	-211.7	75.0	0.1	64.2	62.7
tK	tree Kazakh			-1.5	-1.1	-330.2	-317.1	617.8	24.4	249.0	229.2
ras	rain-agri. steppe			-1.5	-1.7	-185.9	-173.9	2593.8	2959.1	143.6	148.4
rasP	rain-agri. steppe Pontic			-1.5	-1.1	-129.9	-128.4	1095.1	1143.0	119.0	86.9
gs	grass steppe			-0.7	-0.7	-141.4	-127.5	2580.5	2705.8	182.4	181.1
gsdK	grass semi-des. Kaz.			-0.6	-0.1	-73.6	-59.9	1465.5	1410.0	148.8	129.3
gsdS	grass semi-des. South			-3.4	-2.6	43.4	36.7	3043.5	3498.0	377.9	386.8
sdC	shrub desert Caspian			-4.1	-3.4	13.7	16.9	616.6	756.3	180.2	214.1
sdS	shrub desert South			-2.9	-3.0	0.1	6.1	132.9	124.8	41.8	22.8
bdN	bare desert North			-2.4	-2.5	-29.4	-27.2	-269.5	-248.3	-44.9	-53.4
bdS	bare desert South			-4.7	-4.1	-37.3	-38.1	-96.2	-78.4	-49.2	-48.8
		INC [%]		LEN [days]		EOS [days]		DEC [days]		AMP [10°NDVI]	
ira		2.2	2.2	4.3	4.8	0.4	0.4	1.2	0.7	57.7	46.6
tA		9.7	9.5	5.7	5.6	4.8	4.7	-1.8	-1.7	270.0	272.8
tK		5.3	5.0	5.1	4.9	3.6	3.2	5.2	6.5	579.2	610.6
ras		4.6	4.5	0.3	0.8	-1.3	-1.7	1.3	0.9	329.5	327.0
rasP		3.6	3.7	-2.8	-1.7	-4.3	-5.0	3.8	1.0	248.9	204.2
gs		7.1	5.8	-2.1	-1.5	-2.8	-2.7	3.0	2.6	323.9	329.1
gsdK		3.8	2.9	-3.3	0.3	-3.8	-3.3	1.8	1.3	222.3	198.2
gsdS		1.7	2.5	3.5	4.2	-0.4	-1.1	3.6	4.7	334.5	332.1
sdC		1.4	2.2	-8.7	-8.6	-12.9	-13.2	2.4	1.8	166.5	194.9
sdS		0.7	0.5	-1.7	-1.9	-5.5	-5.5	1.8	1.6	41.7	16.1
bdN		-0.2	-0.1	0.7	-1.2	-2.8	-5.4	0.9	0.7	-15.5	-20.4
bdS		-0.5	-0.6	1.7	1.9	-3.6	-4.5	0.6	0.6	-11.9	-8.0

The overall tendencies within the metrics and the sub-regions summarized in Table 3 may be further elucidated in terms of their inter-annual variability in the 1982-2011 period (Fig. 4). SOS, LEN, AMP, BAS, and DEC, characterizing the main features of the phenological dynamics for the selected sub-regions (see Section above I would prefer to merge all cells in the first row and make them gray to suggest that it is ment for all culoms, not just this two) were therefore examined in more detail. These metrics and the sub-regions were selected to provide results for a representative set of sub-regions covering the main eco-regions of Central Asia, using bare desert and shrub desert, grass steppe, rain-fed agricultural steppe, and irrigated agricultural areas.

Another gradient from south to north may be observed within variability: SOS values show a higher variability for the southern part of the study area and for the Caspian lowland deserts. The same holds true for LEN, which is related to SOS, as can be observed in the years in which LEN peaks: 1986, 1995, 1996, 2001, 2007, and others (Fig. 4). In general, Central Asian AMP values have a rising tendency (except in the southern desert), with significant falls for the rain-fed agricultural areas in Kazakhstan (ras). High inter-annual variability of AMP values can be observed since the late 1990s for most of the sub-regions. The BAS of NDVI values exhibit very distinct variations in the Kazakh steppe (both ras and gs) as well as in the Caspian desert (sdC). High peaks in 1983 (1984), 1987, 1993 and 1997 are followed by a drop after 2001. Values for irrigated and bare areas remain without major change. Variations in DEC are low except in agricultural areas (ras) in the north.

Discussion

The trend analyses indicate relatively consistent results compared with other studies [Propastin et al., 2008b; Kariyeva and van Leeuwen, 2012]. However, investigation of individual sub-regions and different phenology metrics reveal that the dynamics of phenology in Central Asia constitute a more complex issue, and some dissimilarities are evident.

The increase in productivity metrics (INT, AMP, MAX) during the vegetation season in grasslands, agricultural areas and tree-covered sub-regions is in accord with other findings of positive trends in NDVI [Propastin et al., 2008b] for all land cover classes. However, this study discloses that this is not the case for bare land-cover classes (bdN, bdS), where only insignificant decreases in productivity metrics were evident. Signs of desertification (not significant) expressed through a decline in all productivity metrics appear in bare areas, mostly around the Aral Sea. This seems reasonable, since the Aral Sea has also contracted within the time-span of the study [Micklin, 2010]. This also provides evidence for the increasing future aridity presumed by Lioubimtseva [2015], already detectable in the results of this work.

The browning, even monotonic, trend in vegetation activity from the north of Kazakhstan reported by de Jong et al. [2013] was not confirmed by this study. MAX value herein had a rising tendency in 10 of 12 sub-regions (significant for 7 sub-regions). It is quite probable that, as Eastman et al. [2013] indicated, increasing NDVI in the green season is balanced by decreasing NDVI in the brown season. This is largely associated with the grassland and shrubland biomes that make up major parts of Central Asia. It appears to be further confirmed by the significant decline in BAS in eight sub-regions with rising productivity metrics.

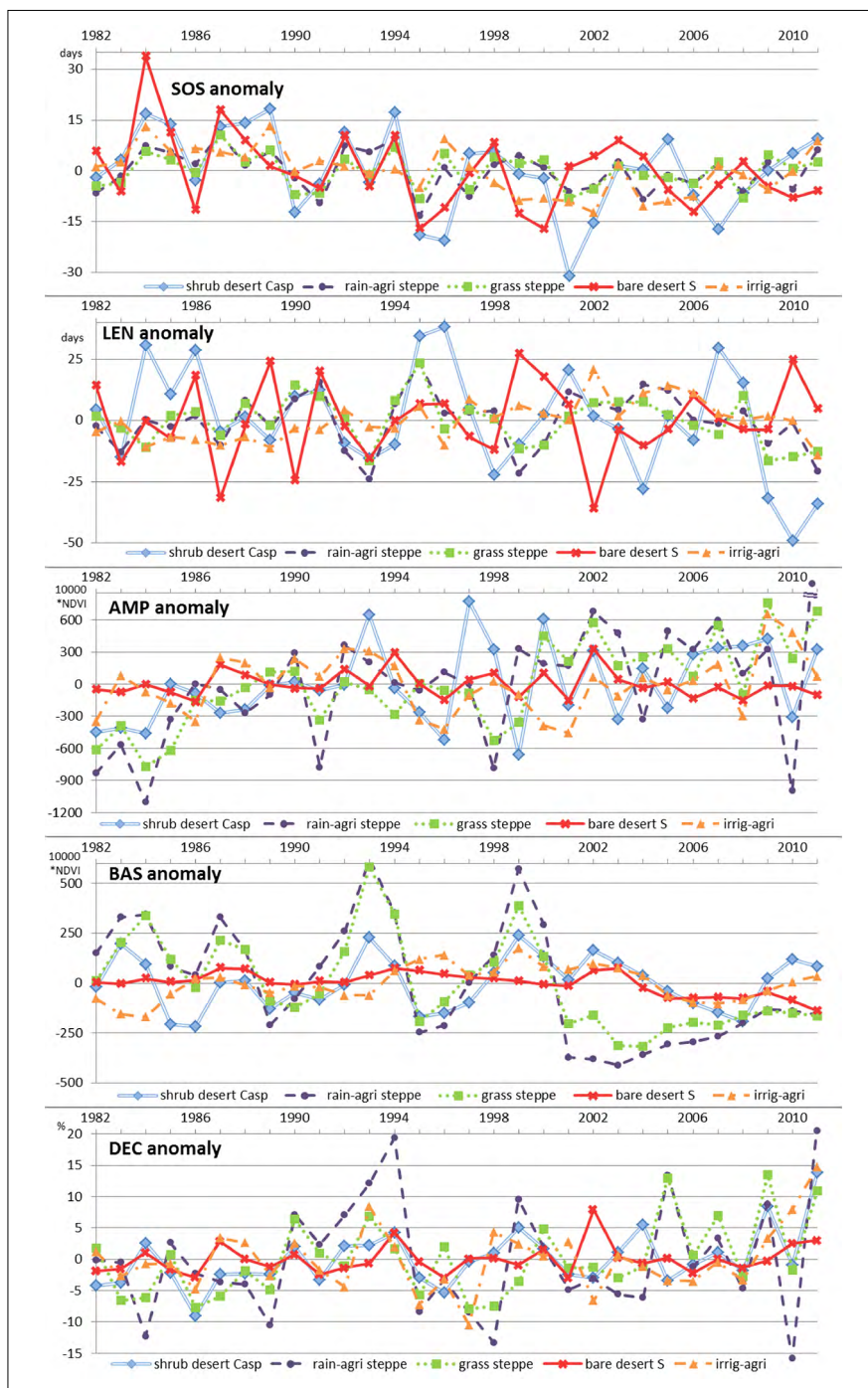


Figure 4 - Variability of selected phenological metrics for five representative sub-regions in Central Asia in the 1982-2011 period. Metrics are expressed as anomalies with respect to the mean for the full period.

SOS values are shifting towards an earlier start in the whole region. However, this is significant only in irrigated areas and the southern Central Asian desert.

Propastin et al. [2008b] reported that a spring rise in NDVI is the main contributor to the seasonal rise in NDVI trend. This study confirms their observations, but reveals certain nuances. The rise is partially related to negative SOS trends in most of the sub-regions, meaning an earlier start for the vegetation season. At the same time, positive INC trends for all sub-regions except bare deserts illustrate more rapid vegetation development.

The analysis in this contribution may be compared with other studies, such as Kariyeva et al. [2012] which is based on the same data source, but uses other settings for processing. The comparison shows the advantages and limitations of remote sensing approaches, influenced as they are by choice of processing parameters. For instance, the SOS values presented by Kariyeva et al. [2012] show an earlier mean start for the vegetation season, by about 15-25 days, compared with this study, which may be related to the different smoothing method and higher threshold value used in our analysis. For most of the area of Central Asia, the two analyses suggest an earlier start to the season. However, a positive slope (towards later SOS), reported mostly from deserts of Turkmenistan and Uzbekistan, was not found in this study (the corresponding sub-regions have no significant negative trends). Both studies report, with some concern, a positive trend in peak values (MAX) of NDVI in major parts of Central Asia. The only differences occur in bare desert areas where negative trends appeared, largely not significant, for MAX metrics as well. On the other hand, the productivity metric for deserts is reported as exhibiting a decreasing slope in Kariyeva et al. [2012], which is consistent with the findings here. Trends in length of season metric vary across the region in both studies, although spatial patterns differ in some areas. Ambiguous results for LEN were also reported in Central Asia by Jeong et al. [2011], at hemispheric level. However, the work in hand shows that a significant positive trend in LEN occurs in irrigated agricultural and tree-covered sub-regions, while a strong and significant shortening of the vegetation season prevails in the Caspian shrub desert.

Several uncertainties must be considered when interpreting a remotely-sensed phenology dataset, arising largely out of limitations in the data used and methodology employed. The GIMMS dataset is one of the most useful sources of NDVI information, but there is no alternative in terms of time-span and global coverage. However, a spatial resolution of 8 x 8 km appears quite coarse even on a regional scale and inevitably leads to mixtures of land cover within one cell. Further, the method of maximum value composites usually suffices in regions with little cloud cover, but for mountainous regions may lead to certain disruptions, with uneven time-spans between composite dates caused by inconvenient atmospheric conditions (mostly clouds). This highlights the importance of the smoothing that must be applied to original NDVI time series. However, uncertainties in filtering methods and derivation approaches to land surface phenology are hard to resolve fully [White et al., 2009; Meier et al., 2015].

The method of specifying a particular metric is crucial for phenology in general and especially so for remote sensing. In this study, one major prerequisite was the selection of a 25% relative threshold for SOS as an optimal value. From that value other metrics (AMP, INT, LEN and EOS) are derived. By their very nature, the metrics are not independent of one another and spurious correlation may exist between some of them (for example MAX and AMP values). Remotely-sensed phenology dataset produced for the region is

not directly comparable with in situ phenology. Such dataset can serve for assessment of complex ecosystem dynamics at regional level but it cannot substitute site- and species-specific phenology observations. The areas of sub-regions must be taken into consideration, as values for sub-regions are averaged for different spatial extents; those with larger areas may be more generalized than smaller ones.

Conclusion

The spatial description and trend analyses of phenology for individual sub-regions indicate results relatively consistent with tendencies found in NDVI-based vegetation studies published on global and regional scales. However, this work offers a better understanding of different aspects of phenology (described by the nine metrics) in homogenous sub-regions of natural and anthropogenic categories of land use. Such a comparison adds more precise and robust information to present knowledge of vegetation dynamics, and draws attention to the complexity of phenology.

The combination of climate and remote sensing data helps provide a better understanding of the impact of climate change on Central Asia. Factors influencing vegetation dynamics have been partially studied and described in several studies. Propastin et al. [2008a] discriminate between human and climatic factors influencing vegetation change. They develop the matter further with descriptions of seasonal temperature and precipitation effects [Propastin et al., 2008b]. Kariyeva and van Leeuwen [2011] extend the range of investigated factors to ten (including non-climate) and compute impacts on major landscapes - desert, steppe and mountain. Gessner et al. [2012] provide detail about the effects of precipitation anomalies on vegetation and their accumulation in the longer term.

All the studies mentioned demonstrate that climate factors, and change within them, have serious and detectable influences on vegetation cover. Climate change is indisputable, and significant changes in vegetation phenology are to be expected [Lioubimtseva, 2015]. A general understanding of the factors and mechanisms that influence vegetation dynamics in Central Asia is a challenge in the prediction of future vegetation scenarios. Climate modelling at global and regional levels has been the object of much intensive work and a comprehensive summary for Central Asia appears in Lioubimtseva and Henebry [2009]. Here, we show that the dynamics of vegetation studied by remote sensing demand consideration of a number of aspects of phenology together with the spatial heterogeneity of a large region. Studying NDVI alone may well lead to generalisations that could lose local specifics. This means that prediction studies will need higher resolution datasets. These may be achieved by applying the methods used in this study to 250 x 250 m spatial resolution NDVI data available from MODIS (Moderate Resolution Imaging Spectroradiometer). However, this became available only in late 2000. It may well offer a better understanding of vegetation dynamics at local level as a starting point for predictions.

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